Hubble Space Telescope Servicing:

A Case Study in Analysis and Presentation of Space Program Risk Information

Vicky Hwa
David Bearden
Jack Maguire

April 16, 2008

Background

- Safety concerns surrounded the loss of the Space Shuttle Columbia and crew
- In mid-2004 NASA cancelled the Hubble Space Telescope (HST) Shuttle Servicing Mission 4 (SM4) previously planned for 2005
- Analysis at this time indicated that without servicing, HST would begin degrading, likely expiring in 2009
  - Estimates based on HST reliability models and battery studies
- NASA embarked the development of other options to service HST
- As part of a decision-making process, NASA Headquarters (HQ) requested a non-advocate review of HST servicing alternatives

Decision Makers and Stakeholders

- NASA Administrator
- NASA Comptroller
- NASA Chief Engineer
- NASA Associate Administrator, Exploration Mission Systems Directorate (ESMD)
- NASA Associate Administrator, Science Mission Directorate (SMD)
- NASA/Goddard Space Flight Center (GSFC) Hubble Space Telescope Program Office
- NASA Independent Program Assessment Office (IPAO)
- NASA Engineering & Safety Center (NESC)
- National Academy of Sciences (NAS)
- Science Community
- Congress – House Science Subcommittee

Situation in mid 2004

- NASA examined options for Hubble Space Telescope servicing without Shuttle
  - Extend mission life without servicing
  - Provide the capability to safely and reliably de-orbit Hubble Space Telescope (HST) at the end of its useful scientific life
  - Provide the capability to robotically extend the scientific life of HST for a minimum of 3 years
  - Enhance scientific capability with new instruments
- GSFC developed baseline concept to study feasibility of robotic servicing mission & Request for Proposal (RFP) to industry
- IPAO/NESC Technical Feasibility Study to assess technical feasibility, cost, schedule of GSFC concept
- National Academy of Sciences (NAS) Study
- Aerospace Corp. Analyses of Alternatives Study

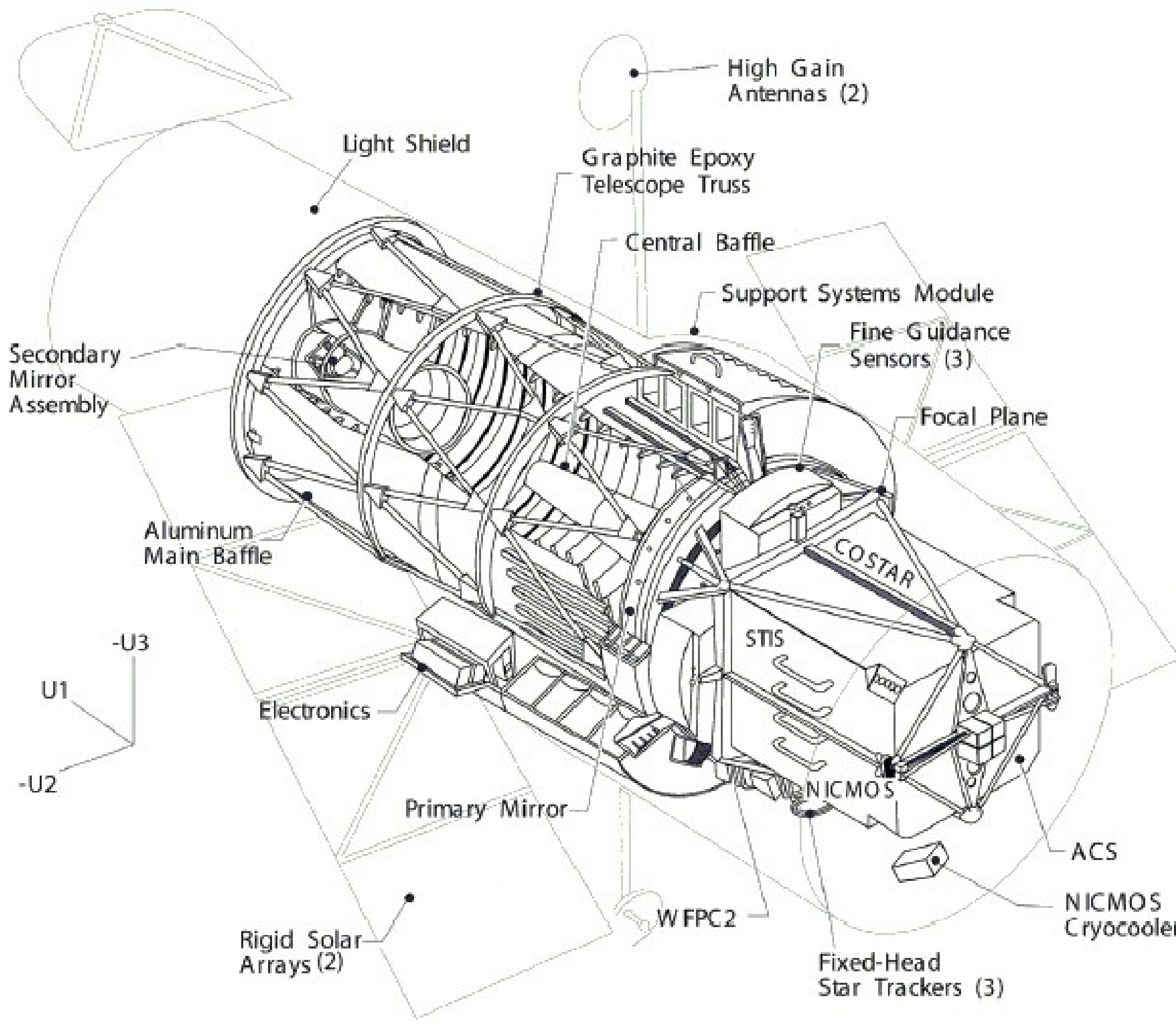
Alternatives Study Overview

- Risk assessment of Hubble Space Telescope (HST) servicing alternatives
  - Alternatives that encompassed a range of options from safe disposal to re-hosting capability on other spacecraft
  - For each alternative assessed: (a) cost and schedule; (b) risk and safety, and (c) capability relative to HST post-SM4 state
- Study Scope
  - Nine week study: June 2004 - Aug 2004
  - Level-of-detail scaled according to available data and schedule
  - Needed to convey aggregate risk information to decision makers
- Include HST science and technical communities
  - Status to and feedback from stakeholders on alternative concepts and Measures of Effectiveness (MOEs)
  - Implications of capability impact on science
  - Accurate data on HST technical constraints, operational state

Hubble Space Telescope Configuration

Hubble Space Telescope (HST)

Weight	24,500 lb
Length	43.5 ft
Diameter	14 ft (Aft Shroud)
Optical System	Ritchey-Chretien design Cassegrain telescope
Primary mirror	94.5 in. dia.
Pointing accuracy	0.007 arcsec for 24 hours
Magnitude range	$5m_v$ to $30\ m_v$ (visual magnitude)
Wavelength range	1,100 to 24,000 Å
Angular resolution	0.1 arcsec at 6328 Å
Orbit	320 nmi, inclined at 28.5 degrees
Orbit time	97 minutes per orbit



HST Science Program

HST Scientific Instruments

WF/PC 2	ACS
NICMOS	FGS
STIS	

HST Observing Program

- 200 GO&AR Programs/year
- 10,000 Exposures/month
- 563 U.S. Astronomers from 33 states *
- 261 non-U.S. astronomers from 28 countries *
- 1,600 registered archival users
- 9 terabytes total archive

*** Cycle 11 results**

Robotic Servicing Decision Tree

- Do nothing to Hubble*
- De-orbit Hubble
  - Service Hubble
    - Batteries and gyros
    - Batteries, gyros, & new instruments
  - Don't service
    - Fly instruments on new platforms
    - Don't fly instruments

*Note: With uncontrolled HST re-entry, the casualty risk (~1 in 250) was estimated to be ~40X greater than U.S. gov't standard (1 in 10,000)

Approach

1. Identify Alternatives

2. Define Measures of Effectiveness

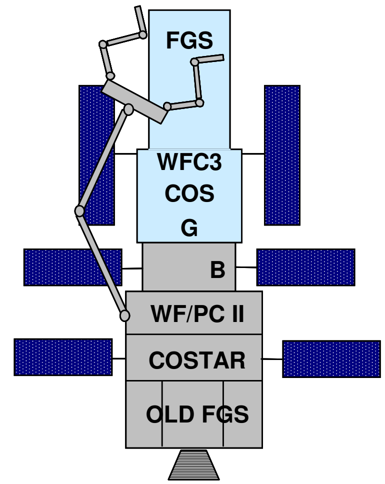
3. Assess Cost & Schedule

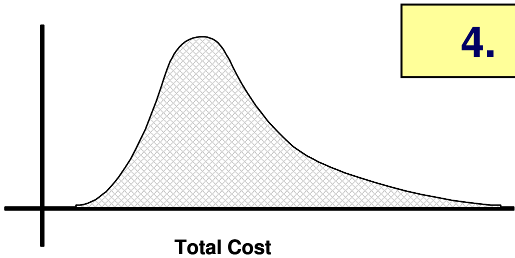
4. Assess Risk and Safety

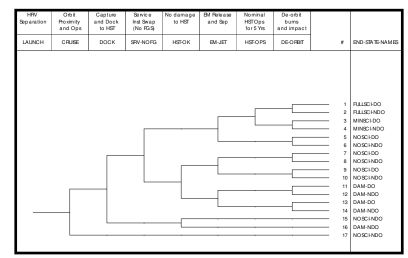
5. Assess Capability Impact

6. Integrate Findings

7. Deliver Final Report







ALTERNATIVE		TASK/COMPONENT: Propulsion	Docking	Arm	Battery	Gyro	WFC3	COS	FGS	A, N & D	Disposal	Orbit	FAMILY
Ground Life Extension	A1-A											L	
Rehost COS LEO	A2-A	B	U					X	X		X	L	RE-HOST
Rehost COS & WFC3 LEO	A2-B	B	U				X	X	X		X	L	RE-HOST
Rehost COS outside LEO	A3-A	B	U					X	X		X	O	RE-HOST
Rehost COS & WFC3 outside LEO	A3-B	B	U				X	X	X		X	O	RE-HOST
De-orbit	B1-A	B	U								X	L	DISPOSAL
De-orbit with Arm	B1-B	B	A	G							X	L	DISPOSAL
Electric Graveyard	B1-C	E	U								X	L	DISPOSAL
Tumbler	B1-D	M	U								X	L	DISPOSAL
Servicer Light	B2-A	M/B	U/T		X	X					X	L	
Goddard no COS	B3-A	M	A	D	X	X	X				X	L	SERVICING
Goddard	B3-B	M	A	D	X	X	X	X			X	L	SERVICING
Goddard with FGS	B3-C	M	A	D	X	X	X	X	X		X	L	SERVICING
Goddard no COS with FGS	B3-D	M	A	D	X	X	X		X		X	L	SERVICING
Cadillac	B3-E	M	A	D	X	X	X	X	X	X	X	L	SERVICING
Boomerang	B4-A	M	A	D	X	X	X	X	X	X	X	L	
Goddard separate deorbit	B4-B	M	A/T	D	X	X	X	X			X	L	
Cling-on	B4-C	M	A	D	X	X	X	X			X	L	
Tug to ISS	C1	E	U								X	L	OTHER
Safe habitat	C2											L	OTHER
Servicing Mission 4	D1											L	

Alternatives Development

- Goal
  - Represent range of variation in cost, schedule and risk
  - Sufficiently broad to ‘cover’ most concepts ‘out there’
  - Emphasize robotic concepts

- Methodology
  - Identify spectrum of alternatives (brainstorming and methodically)
  - Down-select to a handful of representative concepts
  - Define selected alternatives (concept of design, concept of operations, timeline)

- Down-select Criteria
  - Reasonable coverage of trade space including: lowest cost, least impact to HST, most complex, etc.
  - Not an exhaustive coverage of every variation - bounding cases
  - Inclusion of a concept did not imply feasibility or endorsement

Alternatives Assessed

- No Mission
- Rehost
  - On current development
  - New bus
    - Rebuild HST
    - New design
- Disposal
  - Cooperative
    - After science ends
      - Deorbit immediately
    - Before science ends
      - Deorbit immediately
      - Deorbit after science
  - Uncooperative
    - Deorbit immediately
- Service
  - Service Only (With deorbit later)
  - Service and deorbit
    - One stage
      - Stay attached
      - Undock and station-keep
    - Two stages
      - Detach SM, DM stays
- Safe Haven

Rehost Trades:
- Instrument hardware
- Orbit

Disposal Trades:
- Deorbit vs. Graveyard
- Launch on need vs. stationkeep

Robotic Service Trades:
- Degree of autonomy
- Mechanism
- Scope
- Type
- Disposal type

Alternatives Families

- Extension of HST science through non-servicing means
  - A1: Existing HST configuration
  - A2: Rehost in LEO
  - A3: Rehost outside LEO
- Robotic Missions
  - B1: Disposal
  - B2: Servicing (Life Extension Only) with Separate Disposal Mission
  - B3: Combined Servicing (Instruments and Life Extension)
  - B4: Servicing (Instruments and Life Extension) and Attach Later for Disposal
- Other Missions
  - C1: Tug to ISS
  - C2: Safe Haven
  - D1: SM4

All Alternatives Include a De-orbit Mission

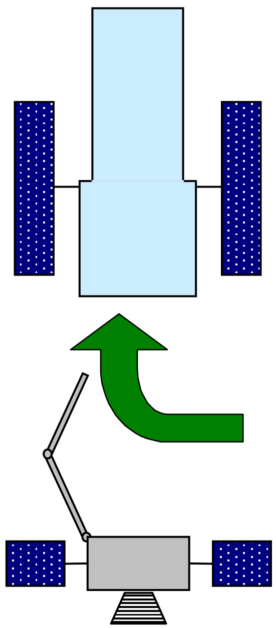
Summary of 21 Alternatives

M = Monoprop, B = Biprop, E = ElectricProp
U = Untargeted docking, T = Targeted docking, A = Grapple arm assisted
D = Dexterous arm, G = Grapple arm
L = LEO, O = Outside LEO
X = Includes task/component
A, N & D = Additional SM4 ASCS, NOBL & DMCSU servicing components

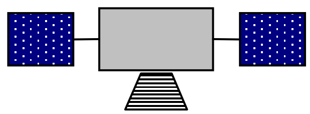
ALTERNATIVE		TASK/COMPONENT: Propulsion	Docking	Arm	Battery	Gyro	WFC3	COS	FGS	A, N & D	Disposal	Orbit	FAMILY
Ground Life Extension	A1-A											L	
Rehost COS LEO	A2-A	B	U					X	X		X	L	REHOST
Rehost COS & WFC3 LEO	A2-B	B	U				X	X	X		X	L	REHOST
Rehost COS outside LEO	A3-A	B	U					X	X		X	O	REHOST
Rehost COS & WFC3 outside LEO	A3-B	B	U				X	X	X		X	O	REHOST
De-orbit	B1-A	B	U								X	L	DISPOSAL
De-orbit with Arm	B1-B	B	A	G							X	L	DISPOSAL
Electric Graveyard	B1-C	E	U								X	L	DISPOSAL
Tumbler	B1-D	M	U								X	L	DISPOSAL
Servicer Light	B2-A	M/B	U/T		X	X					X	L	
Baseline no COS	B3-A	M	A	D	X	X	X				X	L	SERVICE
Baseline	B3-B	M	A	D	X	X	X	X			X	L	SERVICE
Baseline with FGS	B3-C	M	A	D	X	X	X	X	X		X	L	SERVICE
Baseline no COS with FGS	B3-D	M	A	D	X	X	X		X		X	L	SERVICE
Cadillac	B3-E	M	A	D	X	X	X	X	X	X	X	L	SERVICE
Boomerang	B4-A	M	A	D	X	X	X	X	X	X	X	L	
Baseline separate deorbit	B4-B	M	A/T	D	X	X	X	X			X	L	
Cling-on	B4-C	M	A	D	X	X	X	X			X	L	
Tug to ISS	C1	E	U								X	L	ASTRONAUT
Safe habitat	C2											L	ASTRONAUT
Servicing Mission 4	D1											L	

Disposal, Servicing Alternative Configurations

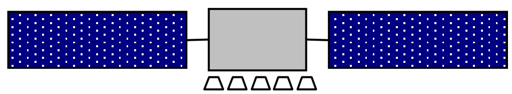
B1: Disposal Only, No Servicing



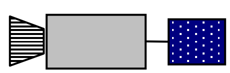
B1-B: DM w/ grapple arm for docking (3400-kg)



B1-A: De-orbit Module (DM) w/o arm for docking (1200-kg)



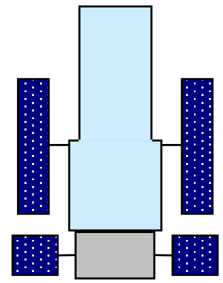
B1-C: Electric propulsion (EP) to disposal orbit (2000-kg)



B1-D: Tumble for drag modulation during final orbits (400-kg)

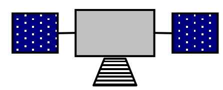
- Electric propulsion tug to disposal orbit (2500-km)
- Small mono-prop "Tumbler"
- De-orbit before 450 km altitude
- Pegasus to Delta-II-class

B2-B4: Robotic Servicing

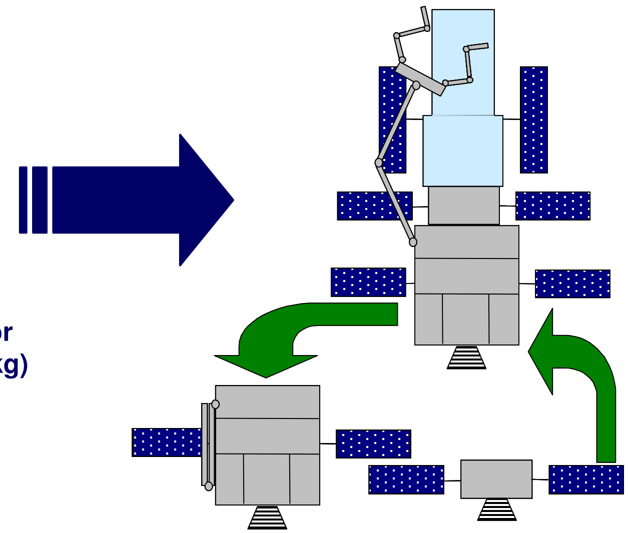


External Servicing for Life Extension (1200-kg)

+



Separate DM (1200-kg)



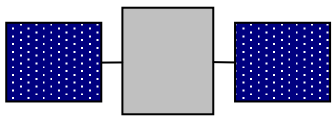
FullSM4Servicing (10000-kg)

Split Missions (9000-kg)

- Minimal servicing (batteries and gyros only) to instruments to full SM4 servicing
- Includes combinations of FGS, COS, WFC3
- Separate de-orbit missions, and options with re-rendezvous for de-orbit
- Minimum and maximum residual mass permanently attached to HST
- No arm and dexterous arm
- Delta-II to Delta IV/Atlas V- class

Rehost, Other Alternative Configurations

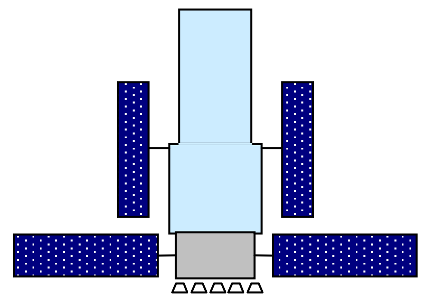
A: COS and WFC3 on Separate Platforms



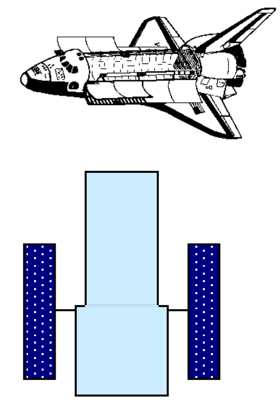
Re-host WFC3 & COS Instrument Capability in LEO or beyond LEO (5500-7500 kg)

- Feasibility not constrained by HST life expectancy
- Includes separate de-orbit mission for HST
- Science gap after HST EOM
- Improved scheduling efficiency beyond LEO
- New program start
- 2.4m aperture
- HST spare primary mirror for LEO, light weight optics beyond LEO
- Duplicate FGS pointing & HST fine-balance reaction wheel capability
- Limited instrument component re-use for environments beyond LEO
- EELV Medium to Heavy

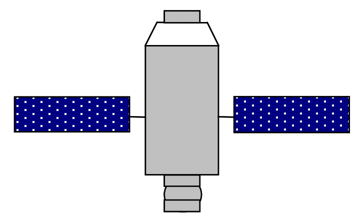
C: Servicing With Shuttle and Safe Haven

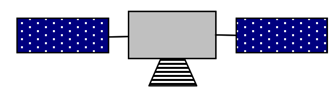


EP tug to transfer HST to ISS (9500-kg)



OR





Launch Safe Haven to Rendezvous with HST, EOL de-orbit mission (19000-kg)

- Shuttle servicing with astronaut safe haven (based on Russian FGB)
- Full SM4 servicing
- Disposal or de-orbit via EP or separate disposal mission
- EELV Medium to Heavy & Shuttle

Measures of Effectiveness (MOEs)

- MOE Categories
  - Cost and Schedule
  - Risk and Safety
  - Capability

- MOEs

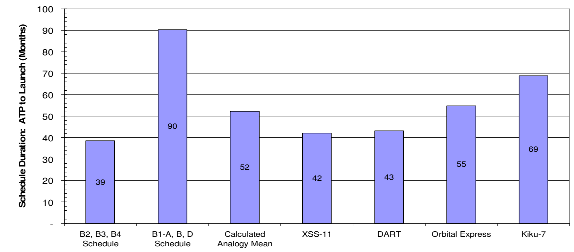
1. Cost	Life Cycle Cost (FY04$B)
2. Schedule	Nominal Development Time (Months)
3. Development Risk	Probability of HST in Required State (%)
4. Mission Risk	Probability of Full Mission Success (%)
5. Capability	Capability Relative to Post-SM4 HST

Cost & Schedule Methodology

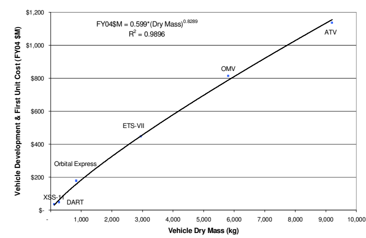
1. Life Cycle Cost ($FY04B)
   - Program Management, Systems Engineering & Mission Assurance
   - Vehicles
   - Robotics
   - Ground System Development
   - Mission Operations & Data Analysis (3 years)
   - De-orbit (if separate)
   - Launch Vehicle
   - Reserves

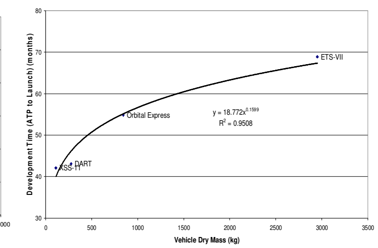
2. Nominal mission development time (months)
   - Time from contract start (or authority to proceed, ATP) to launch

1. Select a set of analogous missions for analyzing alternatives



2. Develop cost and schedule estimating relationships based on actual/projected data

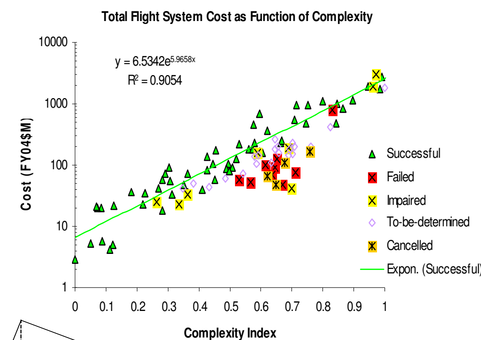


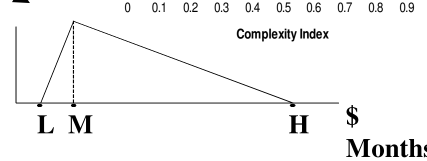


3. Develop cost and schedule estimates using average of viable estimates/models:

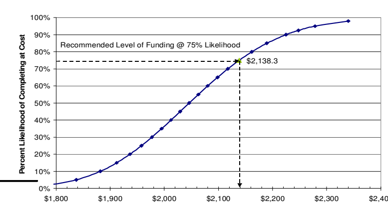
CER and SER, NAFCOM

Complexity Based Estimate





4. Determine cost and schedule triangular risk distributions and develop S-curve



MOE #1 and #2

Risk & Safety Methodology

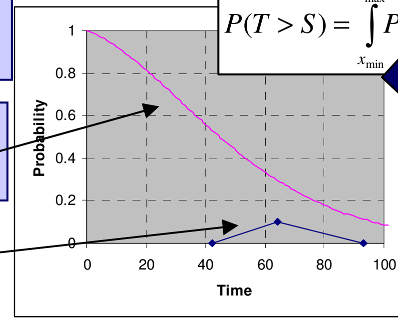
3. Development Risk
   - Risk related to the ability to execute the program on a schedule compatible with the degradation of the HST

4. Mission Risk
   - Risk related to the ability to successfully and safely execute the defined mission, including
     - 3 years of science operations
     - Disposal

1. Establish required condition (RC) for each alternative

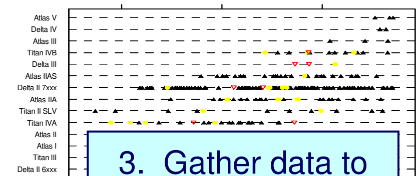
2. Compute P(HST in RC) as a function of time

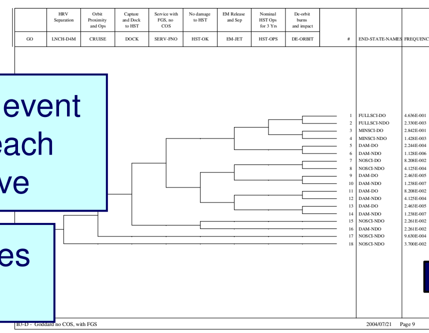
3. Obtain schedule distribution



$$P(T > S) = \int_{x_{\min}}^{x_{\max}} P(T > S \mid S = x) \cdot P(S = x)\,dx$$

MOE #3: P(HST in RC at program completion)





2. Develop event trees for each alternative

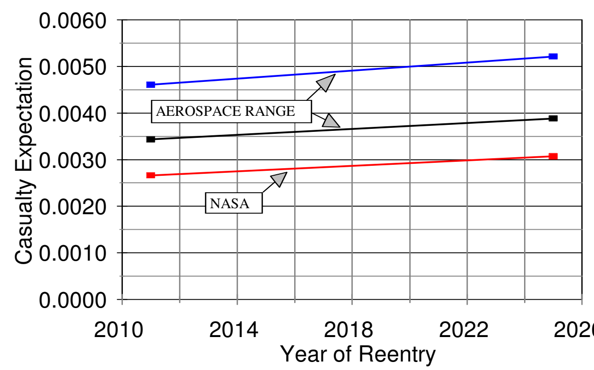
1. Define End-States of interest

3. Gather data to quantify top events

MOE #4: P(Success)

1. Review assumptions in NASA's casualty expectation (CE) calculation

Verified need for controlled re-entry



Capability Assessment Methodology

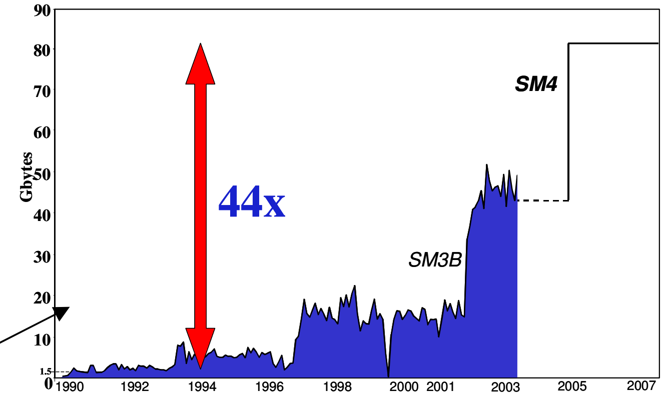
Quantitative Approach

5. Capability Relative To Post-SM4 HST (%)
   - Instrument performance after servicing, relative to post-SM4 baseline (%)

1. Examine historical data for instrument usage patterns when new instruments are installed

2. Develop conversion factor based on historical instrument usage

3. Validate conversion factor based on historical data volume patterns



4. Define instrument suite for each alternative

5. Predict instrument usage for HST after servicing mission

Instrument Usage Allocation Predictions

Instrument	Pre-SM4 *actuals*	B2 *predicted*	B3A *predicted*	B3B *predicted*	B3C *predicted*
ACS	48%	61%	24%	12%	12%
NICMOS	21%	-	10%	5%	5%
STIS	23%	29%	11%	6%	6%
WFPC2	6%	7%	-	-	-
FGS	2%	2%	2%	2%	2%
WFC3	-	-	52%	38%	38%
COS	-	-	-	38%	38%

6. Use post-SM4 instrument allocation to define value of each instrument

MOE #5

Qualitative Approach

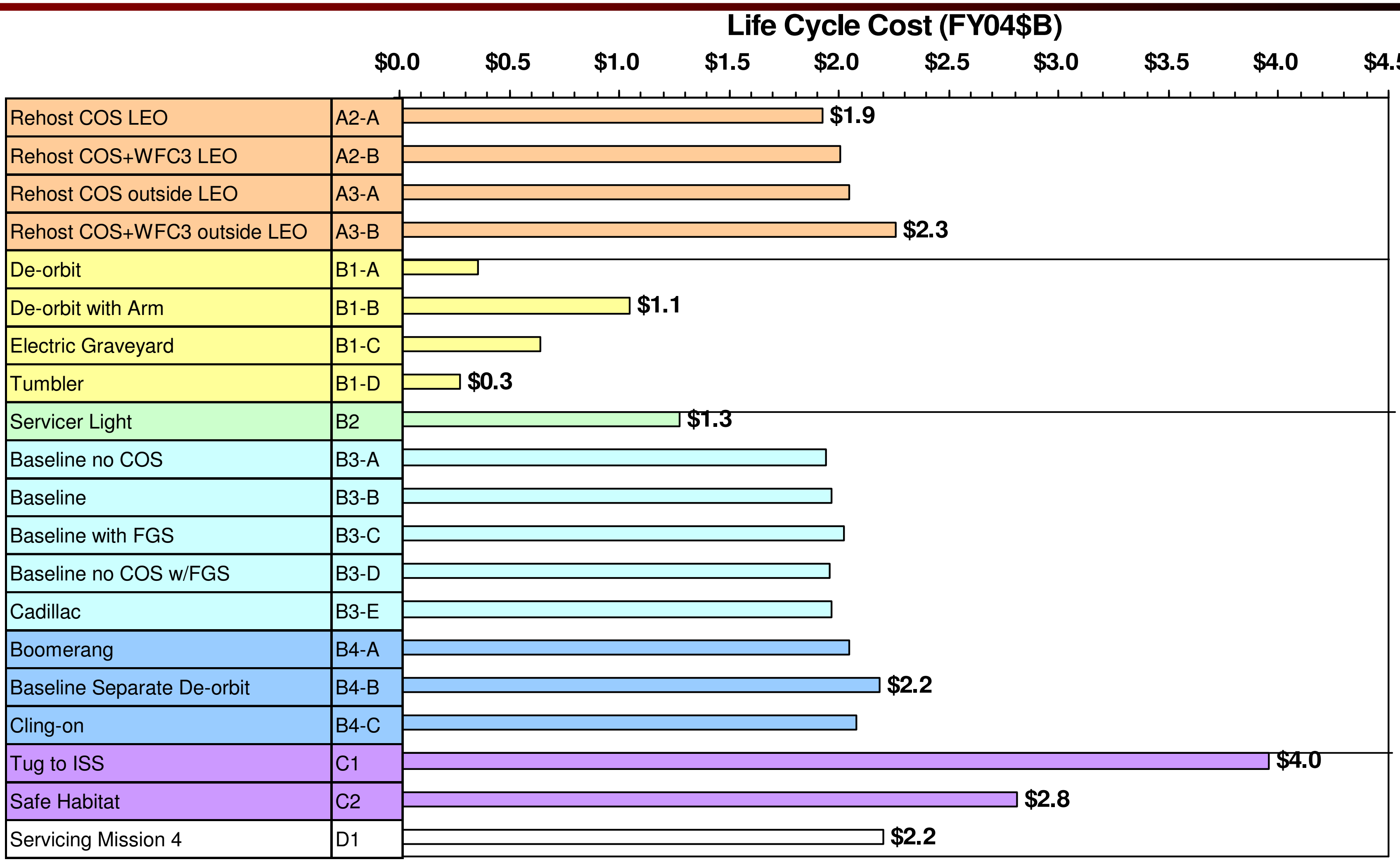
1. Estimated mass properties for each alternative

2. Considered induced dynamic disturbances (e.g. slosh, mechanisms)

3. Considered alternative-unique performance drivers such as ACS

Qualitative comments on jitter performance, control authority, etc.

MOE 1: Life Cycle Cost



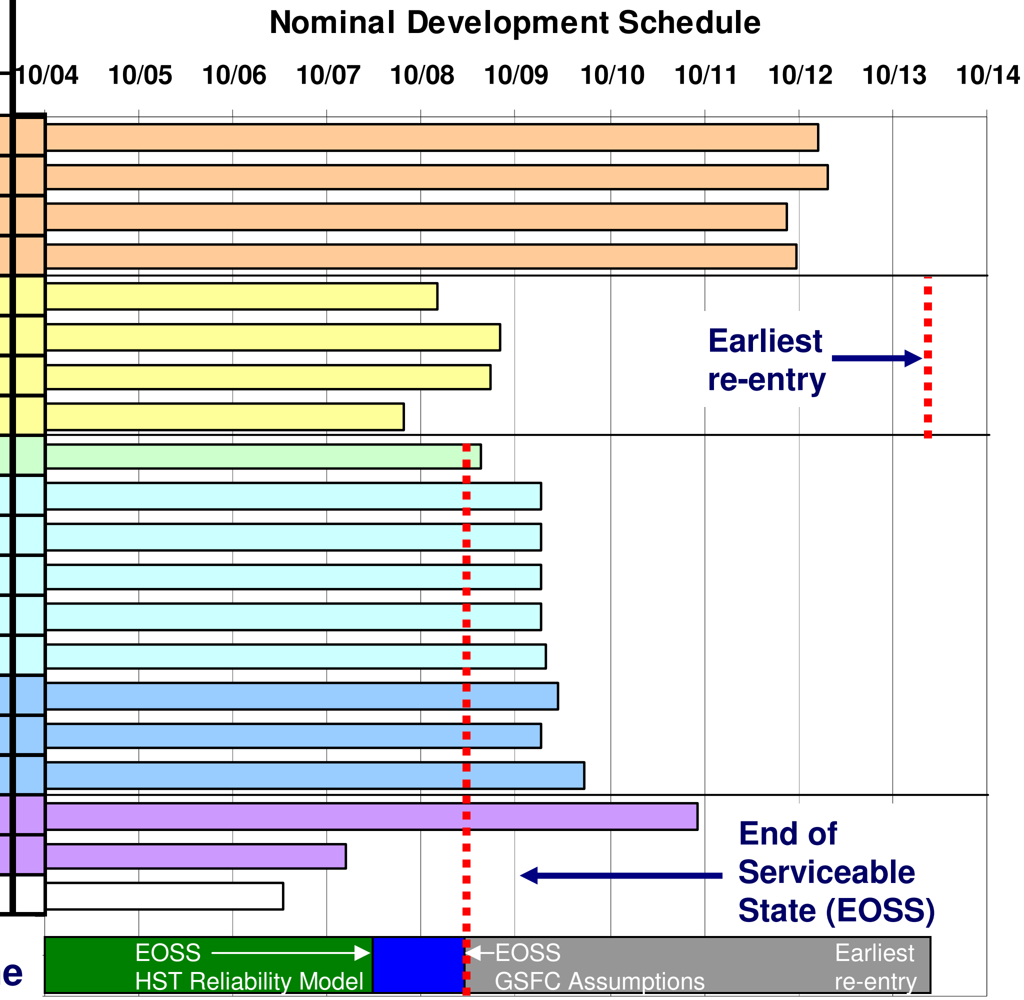
Note: SM4 cost provided by NASA

LCC Estimates Show Little Cost Difference Between Rehost & Servicing Missions

MOE 2 & 3: Schedule & Development Risk

Serviceable state = HST will be able to be restored to full operations using only the replacement parts associated with the current design of the servicing alternative

		ATP to Launch (months)	Prob HST in Serviceable State
		Nominal	P(Success)
Rehost COS LEO	A2-A	100	N/A
Rehost SM4 LEO	A2-B	101	N/A
Rehost COS outside LEO	A3-A	96	N/A
Rehost SM4 outside LEO	A3-B	97	N/A
De-orbit	B1-A	51	1.00
De-orbit with Arm	B1-B	59	1.00
Electric Graveyard	B1-C	58	1.00
Tumbler	B1-D	47	1.00
Servicer Light	B2	57	0.40
Baseline no COS	B3-A	64	0.38
Baseline	B3-B	64	0.38
Baseline with FGS	B3-C	64	0.38
Baseline no COS w/FGS	B3-D	64	0.38
Cadillac	B3-E	65	0.38
Boomerang	B4-A	66	0.38
Baseline Separate Deorbit	B4-B	64	0.38
Cling-on	B4-C	70	0.37
Tug to ISS	C1	85	0.26
Safe Habitat	C2	39	0.59
Servicing Mission 4	D1	31	0.74



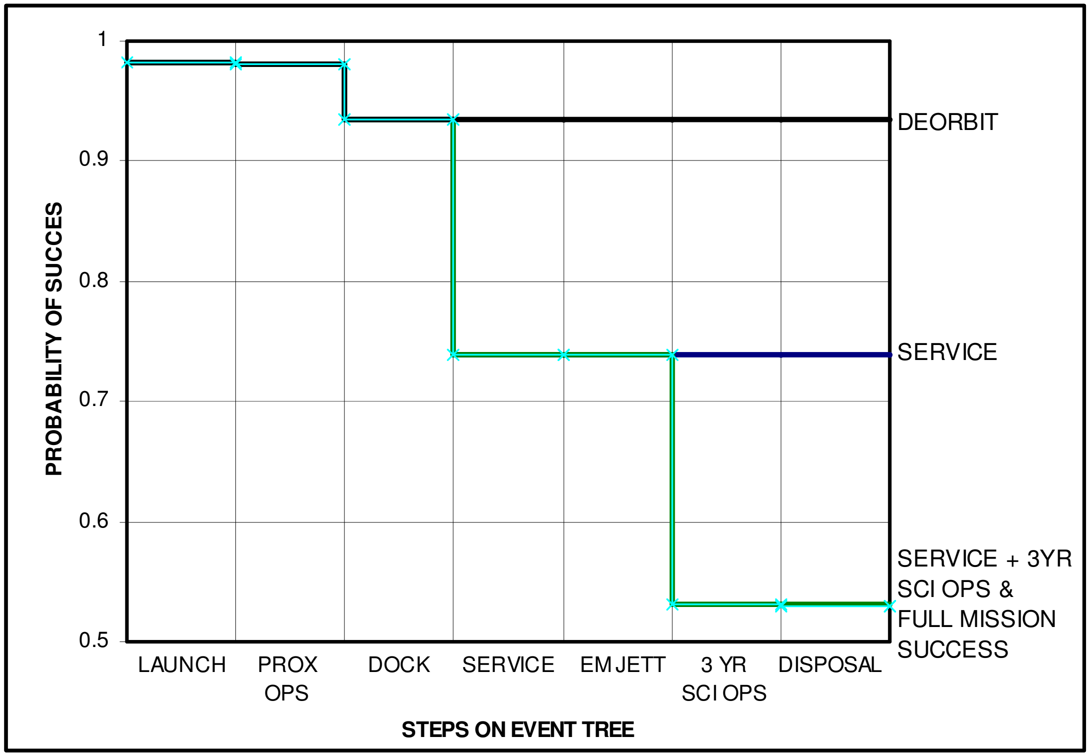
HST Predicted Lifetime

Note: SM4 schedule provided by NASA

MOE 4: Mission Success

		Mission (Serv, Sci, Dispose)
		P(Success)
Rehost COS LEO	A2-A	0.83
Rehost SM4 LEO	A2-B	0.83
Rehost COS outside LEO	A3-A	0.80
Rehost SM4 outside LEO	A3-B	0.80
De-orbit	B1-A	0.89
De-orbit with Arm	B1-B	0.93
Electric Graveyard	B1-C	0.88
Tumbler	B1-D	0.87
Servicer Light	B2	0.58
Baseline no COS	B3-A	0.58
Baseline	B3-B	0.52
Baseline with FGS	B3-C	0.48
Baseline no COS w/FGS	B3-D	0.54
Cadillac	B3-E	0.32
Boomerang	B4-A	0.26
Baseline Separate Deorbit	B4-B	0.47
Cling-on	B4-C	0.52
Tug to ISS	C1	0.43
Safe Habitat	C2	0.63
Servicing Mission 4	D1	0.63

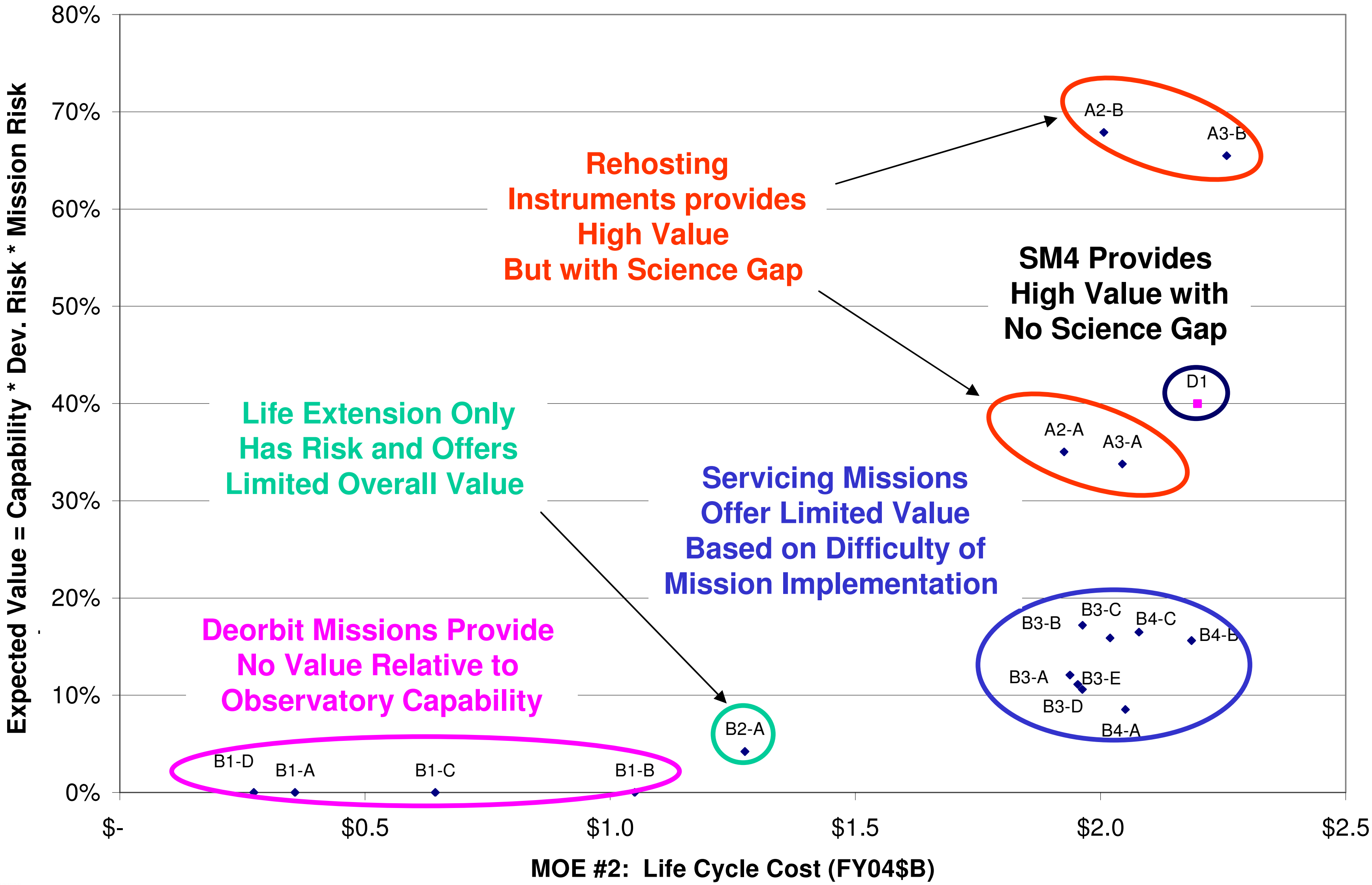
Example Calculation: Baseline Alternative



MOE 5: Capability Relative to Post-SM4 HST

		Capability Relative to Post-SM4 HST	Instruments: WFPC2	STIS	ACS	NICMOS	WFC3	COS	Family
Rehost COS LEO	A2-A	40%						X	REHOST
Rehost SM4 LEO	A2-B	78%					X	X	
Rehost COS outside LEO	A3-A	40%						X	
Rehost SM4 outside LEO	A3-B	78%					X	X	
De-orbit	B1-A	0%	No value						DISPOSAL
De-orbit with Arm	B1-B	0%							
Electric Graveyard	B1-C	0%							
Tumbler	B1-D	0%							
Servicer Light	B2	21%	X	X	X				
Baseline no COS	B3-A	62%		X	X	X	X		SERVICING
Baseline	B3-B	100%		X	X	X	X	X	
Baseline with FGS	B3-C	100%		X	X	X	X	X	
Baseline no COS w/FGS	B3-D	62%		X	X	X	X		
Cadillac	B3-E	100%		X	X	X	X	X	
Boomerang	B4-A	100%		X	X	X	X	X	
Baseline Separate Deorb	B4-B	100%		X	X	X	X	X	
Cling-on	B4-C	100%		X	X	X	X	X	
Tug to ISS	C1	100%		X	X	X	X	X	OTHER
Safe Habitat	C2	100%		X	X	X	X	X	
SM4	D1	100%		X	X	X	X	X	

Expected Value vs. Life Cycle Cost



Findings

- A de-orbit mission is technically and programmatically feasible by earliest re-entry date
  - Suitable robotic docking technologies demonstrated in other programs
  - All propulsive re-entry options reduce casualty expectation to zero
- A robotic servicing and de-orbit mission is high risk
  - HST likely to fall into unserviceable state before robotic servicer could arrive
  - High mission risk due to unprecedented operations and unproven technology
  - Separate servicing and de-orbit missions provide flexibility however, even a minimal servicing mission has high development risk
- Re-host options are technically and programmatically feasible
  - However, there will be a 2-7 year gap in science return, between when HST ceases science operations and a new program can come on line
  - New observatory program would likely compete with ongoing and future observatories for funding
- Astronaut servicing provides highest value and continuity with manageable risk

Conclusion

- Critical assessment that robotic servicing mission: (1) could not be developed in time before HST would lapse into a non-serviceable state; and (2) would undertake unprecedented servicing operations
- Key to success of process was ability to work closely and transparently with internal and external constituencies with varying agendas
- Analysis received unusual visibility, scrutiny and interest at the highest levels of the Government culminating in testimony before the National Academy of Science and Congress
- Risk information presented in an effective way that immediately conveyed many complex inter-related factors
- Contributed to decision to abandon robotic means and put Shuttle servicing back on the table
- Currently targeting August 2008 for fifth (final) space shuttle servicing mission to HST to extend capabilities through 2013 including first ever on-orbit repair of two existing instruments: Space Telescope Imaging Spectrograph (STIS) and Advanced Cameras for Surveys (ACS)